

# Final Report for NASA

## *Parameterizations of the Vertical Variability of Tropical Cirrus Cloud Microphysical and Optical Properties*

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### *Introduction*

Our multi-investigator effort was targeted at the following areas of interest to CRYSTAL-FACE: (1) the water budgets of anvils, (2) parameterizations of the particle size distributions and related microphysical and optical properties (3) characterizations of the primary ice particle habits, (4) the relationship of the optical properties to the microphysics and particle habits, and (5) investigation of the ice-nuclei types and mechanisms in anvil cirrus. Dr. Twohy's effort focused on (1), (2), and (5), with the measurement and analysis of ice water content and cirrus residual nuclei using the counterflow virtual impactor (CVI).

### *Field Phase and Instrument Performance*

Dr. Twohy participated in the entire CRYSTAL-FACE field program, operating the CVI and CPI on the Citation platform and submitting preliminary CVI data to the archive after each flight. The CVI operated well on all flights. Overall, data quality was high with no major problems. The instrument saturated occasionally at condensed water contents (CWCs) greater than  $1\text{-}2\text{ g m}^{-3}$  that were sometimes encountered in the anvils. Total data loss due to this and other (power loss) problems constituted less than 5% of the total flight time. Final CWC data from all flights were submitted to the NASA CRYSTAL-FACE data in a timely fashion.

### *Microphysical Measurements*

The horizontal legs made at a series of altitudes may be used to create contour plots CWC in the anvils. Fig. 1 shows that there is substantial variability in both the horizontal and the vertical. Important features, beside the large variability, are the increase in CWC toward the middle and base of the cloud, and the subsequent decrease below that. With Dr. Gerber, we developed an effective radius parameter ( $r_{\text{eff}}$ ) by combining the bulk CVI CWC with the bulk cloud extinction coefficient from the Cloud Integrating Nephelometer (CIN). Evaluation of the  $r_{\text{eff}}$  parameter in some of the spiral descents made by the Citation showed that ice crystal size tends to increase regularly toward anvil cloud base, peaking at lower altitudes than CWC (Fig. 2). We interpret this to indicate formation and growth of small ice crystals near cloud top, with subsequent sedimentation to lower altitudes and ultimate sublimation in the subsaturated air near cloud base.

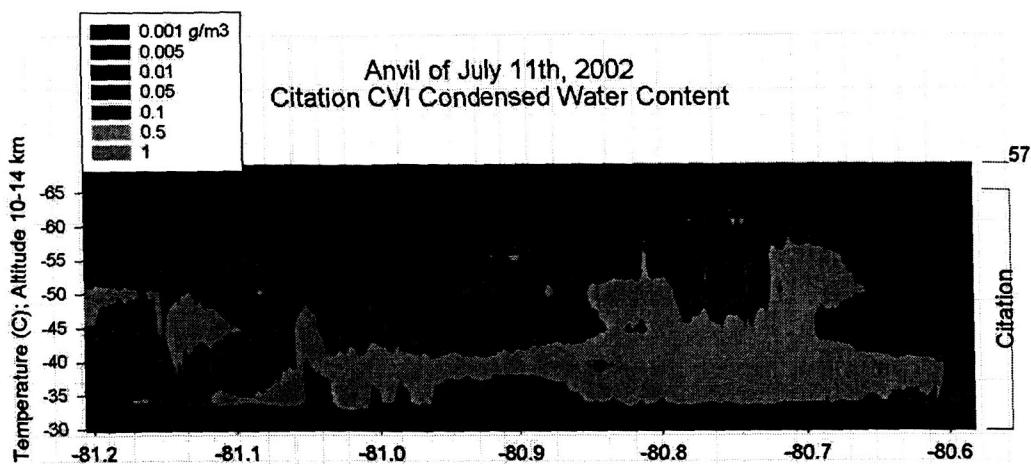


Figure 1. Contours of IWC generated from level flight legs flown by the Citation CVI for anvil case of 11 July, 2002. Horizontal axis is longitude. (Top level data from CU TWC probe on 57-F)

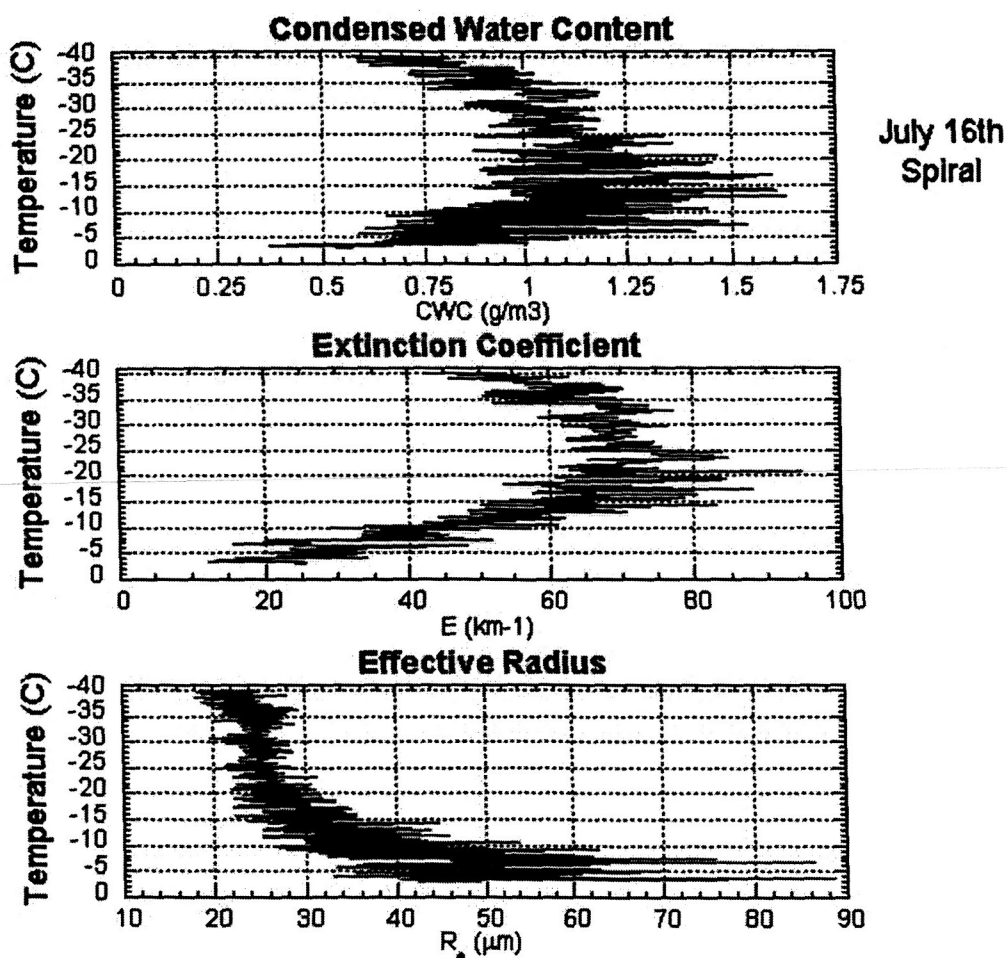
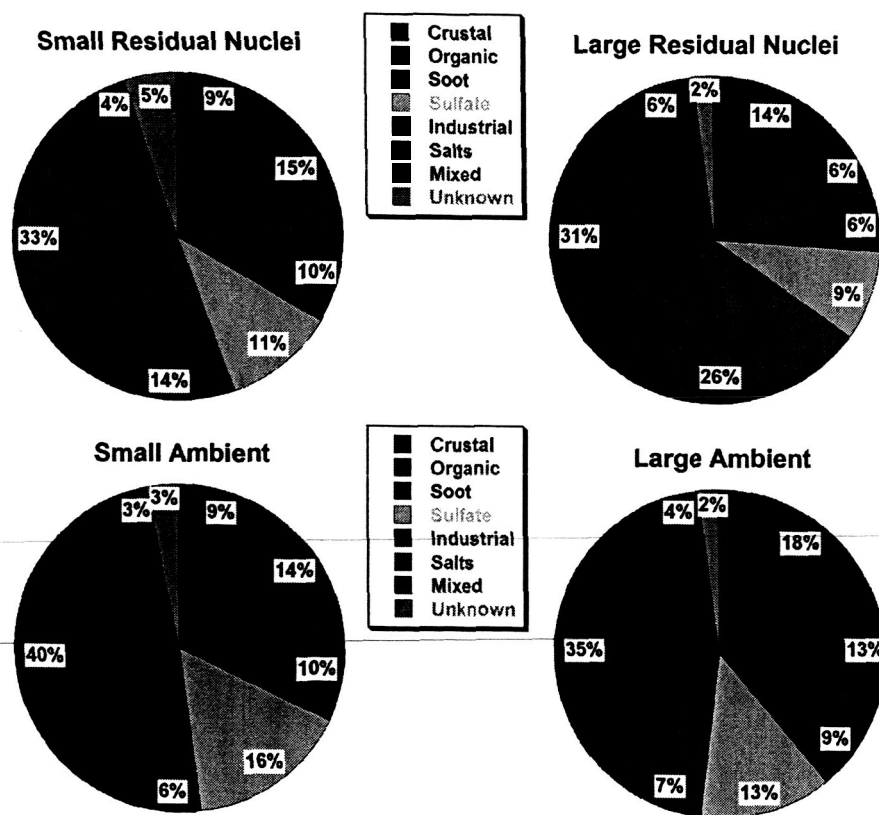


Figure 2. Change in CWC, extinction coefficient, and effective radius with temperature (or altitude) for spiral through anvil of 16 July, 2002.

The CVI CWC data were used by CRYSTAL-FACE researchers in at least six journal publications. These are listed at the end of this report.

### *Ice Nucleation*

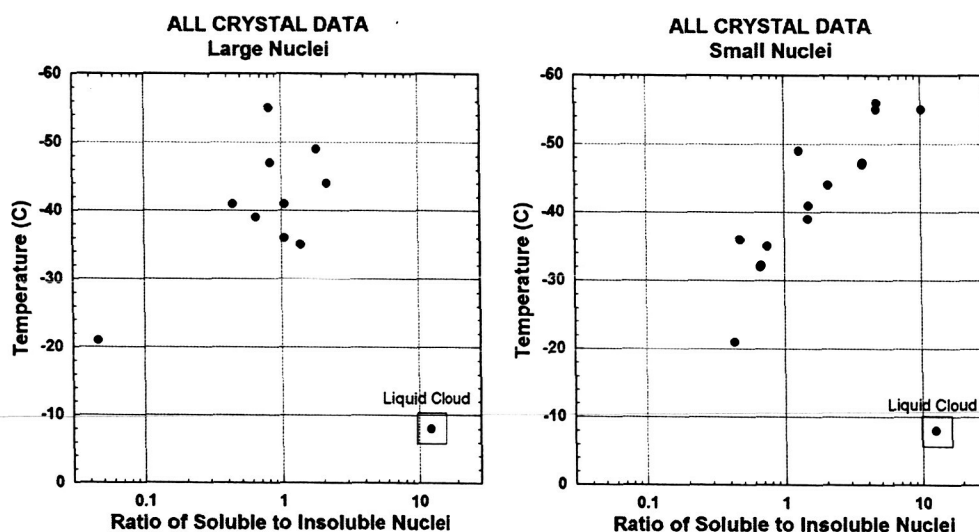
Using the CVI, samples of non-volatile cirrus residual nuclei were collected on electron microscope grids for ten CRYSTAL-FACE cases and analyzed via transmission electron microscopy at Oregon State University. Composition (% by number) of all ice crystal nuclei analyzed are shown in Fig. 3, and were composed of a variety of particle types. In general, larger nuclei had more industrial and crustal material, while smaller nuclei had more organics and soot. Approximately one-third of the nuclei were crustal (mineral dust) or industrial (primarily metals), particles expected to be good heterogeneous ice nuclei. Soluble material like salts and sulfate, thought to produce ice through homogeneous freezing, were present in significant amounts. Carbonaceous particles, both organics and soot, were also present, although their role is less clear.



**Figure 3.** The composition of small and large residual ice nuclei (top left and right) and small and large ambient particles (bottom left and right) collected during CRYSTAL-FACE. Values are percent by number of each composition as determined by X-ray analysis.

The composition of ambient aerosol near and below the anvils was similar to that in the anvil, but was very different from that in the upper troposphere in other regions not influenced by convection. In particular, large numbers of salt particles are present in the near-convective region. This indicates that convection can add to the variability and diversity of aerosol composition in the upper troposphere and influence subsequent cloud formation.

Convection subjects particles to a wide variety of temperatures within a single cloud system, and the type and frequency of ice crystal nucleation is strongly influenced by temperature. Our data, taken at a range of temperatures, shows the influence of these different nucleation mechanisms. In particular, -35 to -40°C is a transition region between heterogeneous freezing processes on solid nuclei and homogeneous freezing on solution droplets. This is shown in Fig. 4. Fig. 4 shows that the ratio of soluble (salts and sulfates) to insoluble (metals and crustal) nuclei increases from low values to more than one at temperatures below -35 to -40°C. At the coldest temperatures, small soluble nuclei are up to ten times more numerous than insoluble ones. This temperature dependence reflects not only the freezing mechanisms but the evaporation, aggregation, and sedimentation processes that occur in the anvil and alter the ratio of soluble to insoluble nuclei over time.



**Fig. 4:** Ratio,  $R$ , of soluble (salts and sulfates) to insoluble (crustal and industrial) residual nuclei as a function of anvil temperature for all CRYSTAL-FACE CVI samples. Left plot shows results for larger nuclei and right plot for smaller nuclei.

The CVI residuals were also provided to the CSU continuous flow diffusion chamber that measures ice nucleating ability. Heterogeneous freezing nuclei with concentrations on order of the large ice crystal concentration as measured by the 2D-C probe were observed. This work is still in progress, but is nearing completion. The CVI nuclei data are being used in at least two journal publications. They are listed at the end of this report.

## *New Particle Formation*

The outflow regions of convective clouds provide ideal conditions for the formation of new aerosol particles through homogeneous nucleation. In the NASA-funded SUCCESS project, we sampled one of the largest nucleation events ever observed and published three related journal papers. The C-F grant provided a small amount of funding to continue working on this project and publish another paper (listed at the end of this report) that extends the calculations and theory related to this case.

### ***Publications Resulting from CRYSTAL-FACE Support*** ***(only journal publications included; multiple conference papers also prepared)***

#### **Related to CVI Condensed Water Content Measurements:**

1. Garrett, T. J., H. Gerber, D. G. Baumgardner, C. H. Twohy, and E. M. Weinstock, 2003: Small, highly reflective ice crystals in low-latitude cirrus. *Geophys. Res. Lett.*, **30** (21), 2132, doi:10.1029/2003GL018153.
2. Heymsfield, A. J., A. Bansemer, C. Schmitt, C. Twohy, and M. R. Poellot, 2004: Effective ice particle densities derived from aircraft data. *J. Atmos. Sci.*, **61**, 982-1003.
3. Heymsfield, A. J., L. M. Miloshevich, C. Schmitt, A. Bansemer, C. Twohy, M. R. Poellot, A. Fridland, and H. Gerber, 2005: Homogeneous ice nucleation in tropical convection and its influence on cirrus anvil microphysics, *J. Atmos. Sci.*, **62**, 41-64.
4. Garrett, T. J., B. C. Navarro, C. H. Twohy, E. J. Jensen, D. Baumgardner, P. T. Bui, H. Gerber, R. Herman, A. J. Heymsfield, P. Lawson, P. Minnis, L. Nguyen, M. Poellot, S. K. Pope, F. P. J. Valero, and E. M. Weinstock, 2005: Evolution of a Florida cirrus anvil, *J. Atmos. Sci.*, in press.
5. Heymsfield, A. J., C. Schmitt, A. Bansemer, G-J. van Zadelhoff, M. McGill, D. Baumgardner, and C. Twohy, 2005: Effective Radius of Ice Cloud Particle Populations Derived from Aircraft Probes, *J. Atmos. Ocean. Tech.*, submitted.
6. Schmitt, C., A. J. Heymsfield, H. Gerber and C. Twohy, 2005: Utilization of equivalent spheres of equal volume and surface area for estimation of the asymmetry parameter from microphysical observations, J.A.M. or G.R.L., in preparation.

#### **Related to Ice Nuclei Measurements**

7. Twohy, C. H. and M. R. Poellot, 2005: Chemical characteristics of ice residual nuclei in anvil cirrus clouds: implications for ice formation processes, *Atmos. Chem. Phys. Disc.*, submitted.
8. Prenni, A. J., P. J. DeMott, S. M. Kreidenweis, S. D. Brooks, C. Twohy, D. C. Rogers, A. J. Heymsfield, M. R. Poellot, 2005: Inferences to ice formation mechanisms in Florida cumuli from ice nuclei measurements of anvil ice crystal residuals, *J. Atmos. Sci.*, in preparation.

#### **Related to New Particle Formation**

9. Clement, C. F., L. Pirjola, C. H. Twohy, I. J. Ford, and M. Kulmala, 2005: Analytic and numerical calculations of formation of a sulphuric acid aerosol in the upper troposphere, *J. Aer. Sci.*, submitted.

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